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भारतीय मानक

ग्रीनहाउस के तापन, संवातन और शीतन की सिफारिशें

Indian Standard

RECOMMENDATIONS FOR HEATING, VENTILATING AND COOLING OF GREENHOUSES

ICS 65.040.30; 91.140.30

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BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

June 1998 **Price Group 6**

Surface Covered Cultivation Structures Sectional Committee, FAD 43

FOREWORD

This Indian Standard was adopted by the Bureau of Indian Standards, after the draft finalized by the Surface Covered Cultivation Structures Sectional Committee had been approved by the Food and Agriculture Division Council.

Development of greenhouse technology in India is of recent origin. Greenhouse technology permits the enhancement of horticultural crop productivity particularly those of vegetables and flowers. This technology is an energy intensive practice. It is therefore essential that adequate guidelines of the environmental control practices are laid down for heating, ventilation and cooling of greenhouses.

In the preparation of this standard, assistance has been derived from ASAE EP 406.2, 1995 Heating, ventilating and cooling of greenhouses, published by the American Society of Agricultural Engineers, USA.

The composition of the technical committee responsible for the formulation of this standard is given in Annex B.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

RECOMMENDATIONS FOR HEATING, VENTILATING AND COOLING OF GREENHOUSES

1 SCOPE

This standard covers recommendations for heating, ventilating and cooling of greenhouses.

2 REFERENCES

The following Indian Standards contain provisions which through reference in this text, constitute provisions of this standard. At the time of publication, the additions indicated were valid. All standards are subject to revision, and parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below:

IS No.	*Title*
2312 : 1967	Propeller type AC ventilating fans
14461 : 1997	Surface covered cultivation structures — Glossary of terms
14462 : 1997	Recommendations for layout, design and construction of greenhouse structures

3 GENERAL DEFINITIONS

For the purpose of this standard, the definitions given in IS 14461 shall apply.

4 PRINCIPLES OF HEATING AND HEAT LOSS DETERMINATION

4.1 Most undesired heat loss from a greenhouse occurs by long wave radiation, conduction and convection, Q_{rc}, and by infiltration, Q_i. Heating requirements are determined by calculating the sum of Q_{rc} and Q_i based upon the natural and mechanical ventilation (*see* IS 14461).

4.2 The greenhouse heat loss by radiation, conduction, and convection, Q_{rc}, (kJ) may be determined by the following equation:

$$Q_{rc} = UA_c(t_i - t_o)$$

where

U = overall heat transfer coefficient (Table 1) kJ/m^{2}°C;
A_c = area of the cover, m^2;
t_i = inside air temperature, °C; and
t_o = outside air temperature, °C.

Table 1 Approximations of Heat Transfer Coefficients for Common Greenhouse Glazing Methods and Materials

Sl No.	Greenhouse Covering	Value of U (kJ/m^2 °C)
i)	Single glass, sealed	6.2
ii)	Single glass, low emissivity	5.4
iii)	Double glass, sealed	3.7
iv)	Single plastic	6.2
v)	Single polycarbonate, corrugated	6.2-6.8
vi)	Single fibreglass, corrugated	5.7
vii)	Double polyethylene	4.0
viii)	Double polyethylene, IR inhibited	2.8
ix)	Rigid acrylic, double-wall	3.2
x)	Rigid polycarbonate, double-wall[1]	3.2-3.6
xi)	Rigid acrylic, w/poly pellets[2]	0.57
xii)	Double poly over glass	2.8
xiii)	Single glass and thermal blanket[3]	4.0
xiv)	Double poly and thermal blanket[3]	2.5

[1] Depending upon spacing between walls.

[2] 32 mm rigid acrylic panels filled with polystyrene pellets.

[3] Only when blanket is closed and well sealed.

4.3 Greenhouse heat loss by infiltration, Q_i (W) may be estimated by considering that the total exchange will be the sum of the sensible and latent energy exchanges:

$$Q_i = iNV[c_{pi}(t_i - t_o) + h_{fg}(W_i - W_o)]$$

where

i = density of the inside air, kg/m^3;
c_{pi} = specific heat of the inside air, J/kg°C;
N = infiltration rate in air changes (Table 2), s^{-1};
V = volume of the greenhouse, m^3;
h_{fg} = latent heat of vaporization of water at t_i, J/kg;
W_i = humidity ratio of the inside air, kg_{water}/kg_{air}; and
W_o = humidity ratio of the outside air, kg_{water}/kg_{air}.

Table 2 Estimated Infiltration Rates for Greenhouses by Type and Construction

(*Clause* 4.3 *and* 4.5)

Type and Construction	**Infiltration Rate (N) per second**
New construction:	
Double plastic film	0.000 21 — 0.000 42
Glass or fibreglass	0.000 14 — 0.000 28
Old construction:	
Glass, good maintenance	0.000 28 — 0.000 56
Glass, poor maintenance	0.000 56 — 0.001 12

NOTE — High winds or direct exposure to wind will increase infiltration rates; conversely, low winds or protection from wind will reduce infiltration rates.

4.4 If outside temperatures are near or below –20°C, and inside humidities are 40 percent or less, latent heat exchange will be limited, and Q_i may be determined as follows:

$$Q_i = 1\,800\,VN\,(t_i - t_o)$$

where

Q_i in watts;

t_i in °C;

t_o in °C;

N in per second; and

V in m^3.

4.5 Natural air exchanges (Table 2) may be very low if cracks become sealed with frozen condensate. During low wind conditions, even unfrozen condensate may serve to seal cracks. The degree to which either will happen will depend upon the type of cover, size, and orientation of the cracks and the inside and outside temperatures.

4.6 The 99 percent winter design dry bulb temperature is recommended for sizing greenhouse heating systems that may be used round the year. A warmer temperature may be selected if use is intended only during warmer season.

4.7 Maximum design heating load shall be based upon the inside temperature required by the plants at night. A temperature of 16°C meets the needs of most plants. To maintain adequate temperature levels for photosynthesis, daytime temperature settings should be generally 6-11°C higher on cloudy days. For all but the coldest climates, solar radiation will generally provide the necessary additional energy to achieve the higher differences specified for sunny days.

5 HEATING SYSTEMS

5.1 Central Heating

5.1.1 Central heating systems generally use hot water or steam distributed to heat exchangers made up of standard black pipe (natural convection), or steam/hot-water unit heaters (forced convection).

5.1.2 Sizing of the heat exchangers is accomplished by standard heat transfer calculations taking into account heating requirements, heating fluid characteristics and exchangers characteristics. Manufacturer's data may be required to get accurate results for finned-pipes and packaged heaters.

5.1.3 Greenhouses 10 m or less in width may be heated with standard black pipe or finned-pipe placed only along the sidewalls. For single-span houses wider than 10 m, distribute the pipes along sidewalls and below/between the crop (or under the benches) in proportion to the expected heat loss for walls and roof, respectively.

5.1.4 If steam is used as the heating medium, heating surfaces shall be installed at least 0.5 metre away from any plant material. For narrow-span ridge and furrow houses, heating pipes should be placed along the exterior walls and below the gutters between sections. Pipes may also be placed below benches, between rows or adjacent to root media for root zone heating.

5.1.5 When using black or finned-pipe, naturally induced air supply does not always provide sufficiently uniform air temperatures at plant height. If increased temperature uniformity is desired, air circulation fans may be installed.

5.1.6 Since maximum heating is required less than 5 percent of the time, central heating system should be designed with two or three zones. The primary zone should be floor or under bench heat. In ridge and furrow houses, the heat pipe under the gutters should be capable of being operated manually to melt snow, if necessary.

5.1.7 All boilers and hot water heaters shall have appropriate valves, controls and safety devices.

5.1.8 If heating pipes are painted with aluminized paint, heat delivery rates will be approximately 15 percent less than from black pipe.

5.2 Packaged Heaters

5.2.1 For low-growing crops on benches or in ground beds, horizontal discharge packaged heaters designed specifically for greenhouse heating may be used without additional circulation fans; however temperature variations in the greenhouse may exceed those in houses with black or finned-pipe heat exchangers. Horizontal air circulation may reduce these variations significantly.

5.2.2 The fans on the packed heaters may be operated continuously to provide improved air circulation. Two heaters with continuously operating circulating fans may be used in houses 20 m or less in length. Heaters should be located in diagonally opposite corners discharging toward the far walls in a direction parallel to the sidewalls.

5.2.3 For houses longer than 20 m but less than 40 m heater fans alone may not be sufficient to maintain air circulation patterns. In this case, it is recommended that two additional fans be placed at the middle of the greenhouse, one on each side, to aid air circulation. Alternatively, additional heaters may be positioned to achieve the same result, with the size of the original heaters reduced in proportion to the capacity of those added.

5.2.4 Direct-fired heaters shall be provided with outside air for combustion.

5.2.5 All gas or oil-fired heaters shall be vented outside in accordance with manufacturer's recommendations using stack equipped with weather caps. The use of vented heaters (to take advantage of the carbon dioxide produced) is not recommended because of the potential for generation of toxic gases due to incomplete combustion and/or burning of contaminated fuels. It is also generally true that periods of high heat demand (usually non-daylight hours) do not coincide with periods when carbon dioxide enrichment may be applied effectively (that is, during daylight). Carbon dioxide enrichment, if desired, may be accomplished.

5.3 Bench Heating

5.3.1 Bench heating may be used to provide optimum temperatures in the root zone for seed germination, propagation and general plant growth. It may also be used to reduce heating costs if the air temperatures may be lowered to compensate for higher root zone temperatures.

5.3.2 Hot water at temperature of 35-40°C is generally circulated through 13 mm polyethylene and PVC pipe or tubing. For maximum temperature uniformity, the pipes or tubes may be configured in a series of loops with the supply and return headers located at the same end of the bench to allow the temperature gradient in the first half of each loop to cancel the gradient in the second half. Pipe/tube spacing may be approximately 100 mm.

5.3.3 The pipe or tubing loops may be placed directly on the bench or attached underneath. Polystyrene insulation board placed immediately below the pipe or tubing will ensure that most of the heat is directed into the root zone.

5.3.4 Temperature uniformity may be improved, if necessary, by decreasing the spacing of the pipes/tubes or by adding a 25-30 mm layer of wet sand over and around the pipes/tubes. If sand is used, provision may be made to retain the moisture by covering the sand with a perforated plastic film.

5.4 Floor Heating

5.4.1 Floor heating is considered good practice where plant containers are set directly on the floor. It is particularly well suited where a minimum amount of protection is needed, as in over-wintering houses for hardy shrubs. It may also be used to some advantage in supplementing conventional heating systems, subject to the considerations outlined below and the understanding that the time constants associated with floor heating are generally larger than those for conventional systems. When used, floor heating may be configured as the first stage of heat.

5.4.2 Either loose gravel, porous concrete (concrete without sand), solid concrete or sand may be used for the floor material. A floor thickness of 75-100 mm is generally recommended. If solid concrete is used, the floor should be sloped for drainage. Sand floors should be covered with perforated plastic to retain moisture (to promote heat transfer between the pipes and the sand).

If ground water is within 1.8 m of the floor, 25-50 mm extruded polystyrene insulation board should be installed below the floor.

5.4.3 A typical installation circulates 35-40°C water at velocities of 0.6-0.9 m/s through 20 mm polyethylene, polyvinyl chloride or polybutylene pipe embedded in the floor. The pipes may be configured in a series of loops, up to 120 m per loop, with one end of each loop connected to a supply header and one to a return header.

5.4.4 Pipe spacings of 0.3 metre on centre in a porous concrete floor will provide approximately 50 Watt/m^2 of floor area to the greenhouse when the floor is completely covered by plants. Hot water may be supplied or it may be from a zone of hot water system for heating the greenhouse. If separate, the 50 Watt/m^2 may be used to size the heater, and the main system capacity may be reduced accordingly.

5.5 Heating Controls

5.5.1 Heating controls and sensors shall be capable of withstanding extreme humidity and dust conditions.

5.5.2 Sensors may be continuously aspirated at a speed of 3.0 to 5.0 metre per second to reduce temperature gradients in the vicinity of the sensors. Aspirator fans shall have totally enclosed motors and shall pull the air across the sensors to avoid temperature measurement errors due to addition of motor heat to the air stream.

5.5.3 The control sensors shall be fully shaded from direct solar radiation in glass-covered houses and from both direct and diffuse solar radiation in plastic-covered houses. The material used to shade the sensors shall have a low thermal conductivity and shall be painted or coated white on the side(s) facing external radiation to minimize energy absorption.

5.5.4 Sensors may be located near the centre of the growing area. The location may be representative of that occupied by the plants and may not be unduly affected by heating and ventilating systems.

6 AIR CIRCULATION SYSTEMS

6.1 Perforated-Tube Air Circulation

6.1.1 Air circulation is essential for minimizing carbon dioxide, temperature, and moisture gradients in closed greenhouses. Overhead perforated plastic tube systems may be useful for this purpose, although at reduced efficiency compared to horizontal flow. This tube is generally connected directly to the outlet of a fan which forces air down the length of the tube and out through appropriately spaced discharge holes. If the system is used to distribute heat, packaged heaters are typically installed at the inlet end of the tube system, and the exhaust air of the heaters is directed into the inlet of the fan.

6.1.2 Discharge holes are generally located on the opposite sides of the tube and are typically spaced half to one metre apart along the axis of the tube, depending upon tube diameter and length.

6.1.3 The tubes should be sized to handle a flow rate of 1/4 to 1/3 of the greenhouse air volume per minute with an air velocity at the entrance of the tube of 5 to 6 m/s. The total area of the discharge holes shall be one and half to two times the cross-sectional area of the tube.

6.1.4 The discharge holes shall be so arranged that the air is not blown directly into the plants.

6.1.5 One tube is generally sufficient for greenhouses 10 m or less in width. Two or more tubes are necessary for wider greenhouses.

6.1.6 Circulation tubes shall not exceed 50 m in length. Best distribution occurs when the length is 30 m or less.

6.1.7 The warm air discharge from each packaged heater may be directed behind the plastic-tube air circulation fan. The capacity of the circulation fan shall be equal to or greater than the heater fan capacity.

6.1.8 Air circulation fans may be run continuously during the heating season and whenever exhaust fans are not running during the cooling season to minimize moisture and temperature gradients within the greenhouse.

6.2 Horizontal Air Circulation

6.2.1 Horizontal air circulation consists of air circulated in a horizontal pattern (in 'racetrack' fashion) above the plant canopy using large-diameter, low-power propeller fans. Reduced fan pressures, reduced maintenance (no tubes to replace) and lower initial costs make this a more efficient method of air circulation and/or heat distribution compared to perforated-tubes.

6.2.2 In ridge and furrow greenhouses, circulation may be directed down one section and back through another. Fans shall be located over the crop in each section.

6.2.3 In single-span greenhouses, fans may be installed with their axes parallel to the long dimension of the house at a distance of one fourth the house width from the sidewalls. The air may be circulated parallel to the sidewalls down along one side and back along the other.

6.2.4 Fans may be mounted perpendicular to the ground and shall be at least half to one metre above the plants. If the fans are higher than one metre, they tend to move the air above the canopy but not within the canopy. Guards shall be provided to protect personnel from the propellers.

6.2.5 The fans shall be placed along the direction of air movement at spacings of not more than thirty times the fan diameter and about 5.0 m from end walls.

6.2.6 Fans shall be selected to provide an air flow of 0.01 $m^3/s.m^2$ of the floor area. Fan mounts shall be designed to allow adjustment of the fans to ensure that local velocities in the vicinity of the canopy do not exceed 1.0 metre per second.

7 CARBON DIOXIDE LEVELS

7.1 Depletion of carbon dioxide (CO_2) levels below the normal atmospheric concentrations of 350 ppm may commonly occur on clear, cold winter days. Since CO_2 levels below 350 ppm may retard plant growth, whereas levels in excess of 350 ppm to 2 000 ppm on an extended basis and as much as 5 000 ppm for short periods of time may increase growth, addition of CO_2 to the greenhouse atmosphere is a recommended practice during winter.

7.2 Carbon dioxide may be obtained from liquid carbon dioxide in tanks or by the unvented burning of fuel gases (natural gas, liquid propane or liquid butane) in units specifically designed and maintained for the purpose.

7.3 If CO_2 is generated from the unvented burning of fuel gas, the fuel shall not include excessive impurities and it should be ensured that adequate air is available for complete combustion. Impurities likely to cause trouble are organic nitrogen compounds, ethylene and propylene. The former two are normally controlled to within acceptable limits in commercial fuel gases;

however, propylene may be major constituent of liquid propane. Since propylene injury mimics that of ethylene, a by-product of incomplete combustion, unburned propylene escaping into the house through loose connections in the feed line may produce symptoms suggestive of combustion problems. Incomplete combustion may be detected using carbon monoxide detectors and alarms.

7.4 In addition to fuel impurity concerns, water production in carbon dioxide generation from burning fuel gases may lead to difficulties. In pure form, natural gas, methane, will yield one volume of carbon dioxide and 2 volumes of water vapour for each volume of gas burned, propane will yield 3 volumes of CO_2 and 4 of water vapour for each volume of gas burned. The actual yield of carbon dioxide and water vapour obtained in the practice may differ from these values somewhat since commercial grades of fuel gases are rarely available in pure form.

7.5 The amount of CO_2 required to maintain 350 ppm in a closed greenhouse is low where only the quantity consumed by the plants need be replaced. However, the amount necessary to elevate carbon dioxide levels above 350 ppm will vary depending upon the tightness of the house, outside wind speed and the level of carbon dioxide desired. For a greenhouse with an infiltration rate of one air-exchange per hour under normal wind conditions, a carbon dioxide injection rate of approximately 0.003 $m^3/h.m^2$ of floor area will maintain a level of about 1 000 ppm in a fully cropped house. An injection rate of 0.004 3 $m^3/h.m^2$ may be expected to maintain a level of about 1 500 ppm under the same conditions.

7.6 Carbon dioxide alarms shall be employed whenever carbon dioxide is being added to a greenhouse. CO_2 levels greater than 5 000 ppm exceed safety limits for extended periods of moderate human activity (lifting, bending, walking).

7.7 Carbon dioxide enrichment may not be practiced when ventilation rates exceed 0.02 $m^3/s.m^2$ of floor area. Carbon dioxide depletion level is generally not a problem at ventilation rates that are high, and the quantity of carbon dioxide required to elevate carbon dioxide levels under those conditions generally makes enrichment uneconomical. The advisability of enrichment at lower rates of ventilation will depend upon level of carbon dioxide desired and the cost of carbon dioxide.

8 NATURAL VENTILATION SYSTEMS

8.1 Natural ventilation is a direct result of pressure differences created and maintained by wind or temperature gradients, and it depends heavily on evapotranspiration cooling provided by the crop to maintain acceptable temperatures within the greenhouse. Its suitability as a primary means of cooling shall be judged based on local environmental conditions, type of crop grown and the design of the greenhouse.

8.2 Natural ventilation may be used to advantage in moderately warm climates or in hot, arid climates, depending upon the availability and dependability of the wind. Crops capable of high rates of transpiration should be chosen to maximize evapotranspiration cooling.

8.3 Greenhouses should be provided with vent openings on both sides the ridge and on both sidewalls. Vent operation should be such that the leeward vents are opened to produce a vacuum at the top of the ridge. Opening of the windward vents produces a positive pressure in the house which is typically less efficient than the vacuum operation.

8.4 Pressure gradients are typically small so that the large vent openings are necessary to provide adequate ventilation. The combined sidewall vent area should equal the combined ridge vent area, and each should be at least 15 to 20 percent of the floor area.

8.5 Ridge vents should be top-hinged and should run continuously the full length of the greenhouse. The vents should form a 60° angle with the roof when fully open.

8.6 Automatic vent system should be equipped with rain and wind sensors to permit closing during periods when crop or ventilator damage might occur.

9 FAN VENTILATING AND COOLING SYSTEMS

9.1 Basic Considerations

9.1.1 As a general rule, greenhouse temperatures should be limited to less than 30 to 32°C. An upper limit of 35°C may be considered from the stand point of worker comfort and safety.

9.1.2 Present cooling alternatives for greenhouses depend upon exhaust fans to remove excess energy. As outside air is brought into and then through the house, its temperature rises due to sensible heat gain from the canopy, ground and surrounding structure. The volume of air required to maintain temperature rise, may be estimated by following equation:

$$(1-E)tlA_f = U\,A_c\,(t_i - t_o) + \frac{Q_v\,A_f\,C_{p\,outlet}}{V_{outlet}}\,(t_{outlet} - t_{inlet})$$

where

E = evapotranspiration coefficient, dimensionless;

t = solar transmissivity of cover, dimensionless;

I = solar radiation, Watt/m^2 of floor area;

A_f = floor area in m^2;

V_{outlet} = specific volume of air leaving greenhouse, m^3/kg air;

Q_v = ventilation rate, m^3/s.m^2 of floor area;

$C_{p\ outlet}$ = specific heat of air leaving greenhouse, J/kg.°C;

t_{outlet} = temperature of air leaving greenhouse, °C;

t_{inlet} = temperature of air entering greenhouse, °C;

t_o = outside temperature; and

t_i = inside temperature.

9.1.3 The terms U, A_c, t_i and t_o in the equation are the same as mentioned under **4.2**. The inside air temperature (t_i) should be taken to be the average of the inlet and outlet temperatures [(t_{outlet} + t_{inlet})/2]. The overall heat transfer coefficient, U, may be obtained from the equation given in **4.2**. The specific volume (V_{outlet}) and specific heat ($C_{p\ outlet}$) of the air leaving the greenhouse may be determined from the psychometric relationships given in Annex A.

9.1.4 Solar transmissivity, t, may be taken as 0.88 for single layer covers or 0.79 for double layer covers with little error. Observations suggest that the net solar gain may be as little as 50 percent of that incident on a horizontal surface outside for older greenhouses with numerous structural and heating equipments positioned overhead.

9.1.5 Solar radiation, I, may be estimated, for a given latitude, as solar intensity on a horizontal surface at solar noon on July 21, corrected for atmospheric clearness. Outside dry bulb and wet bulb temperatures for a given location may be estimated using the one percent summer design values.

9.1.6 The evapotranspiration coefficient (E) may vary between 0.0 and 1.0, depending upon the type, amount, age, health, and/or stress level of the crop, the humidity ratio of the ventilation air at the inlet, and the amount of moisture available for evaporation from non plant sources within the house. Very young plants without fully established root systems, stressed plants, very old, or diseased plants, plants that exhibit low daytime transpiration rates (for example most succulents), and high inlet humidity ratios will all tend to decrease E. Water evaporated within the house from wet floors, free standing water, and/or fog cooling shall be accounted for by increasing E. Evaporative pad cooling, on the other hand, reduces E by increasing inlet humidity ratio.

9.1.7 For most of the crops, a small amount of plant material, leaf area index (LAI) less than 1.0, dry floors and inlet humidity ratios more than 0.017 kg$_{water}$/kg$_{air}$ (as might be expected with evaporative pad cooling) are likely to produce E values in the range of 0.1 to 0.2. Similarly, a large amount of healthy, stress-free, mature plant material, LAI more than 4, wet floors and an inlet humidity ratio less than 0.015 kg$_{water}$/kg$_{air}$ (for example no evaporative cooling) may produce E values as high as 0.8 to 0.9.

NOTE — Leaf area index (LAI) of the crop is defined as the total leaf area of all plants divided by the total floor area of the greenhouse.

9.1.8 Air velocities in greenhouses with air inlet to fan distances of less than 30 m may be insufficient for adequate heat transfer even though equation given in **9.1.2** is satisfied. In these cases, air flow rates should be increased according to :

$$Q_{adj} = \frac{C\,Q_v}{D}$$

where

Q_{adj} = adjusted ventilation rate in m^3/s.m^2,

D = inlet-to-fan distance in m, and

C = 5.5 in SI units.

9.1.9 Size of ventilation fans may be selected in order to deliver the required flow rate at 15 kPa static pressure when all guards and louvers are in place, unless specific design criteria require delivery at higher static pressures; for example, insect screens or evaporative pads.

9.1.10 Fans shall be spaced not more than 8 m apart along the sides or ends of the greenhouse. Wherever possible, fans should be located on the leeward sides or ends. If the fans are to be located on the windward sides, ventilation capacity shall be increased by at least 10 percent.

9.1.11 A distance of 4 to 5 fan diameters should be maintained between the fan discharge and any nearby obstructions. Fans may be mounted in the roof if obstructions interfere with other mountings; however, the following trade-off may be considered before selecting this option. In cold climates, roof mounted fans increase infiltration rates due to air leakage through the louvers, and the possibility exists that the fans may become inoperable due to sealing of the louvers through frozen condensate and/or precipitation. Roof mounted fans also generally increase the chances of precipitation leakage and shading.

9.1.12 Exhaust fans shall have freely operating louvers, if mounted on the inlet side of the fan, or motorized louvers if mounted on the outlet side, so that unwanted air exchange is prevented when the fans are not operating.

9.1.13 Air inlet louvers or shutters shall open outward. They may be motorized and wired to open during fan operation. Louver area should be at least 1.25 times the area of the fan, unless additional criteria requires otherwise.

9.1.14 Guards shall be used on fans to prevent accident. Use manufactured guards or install woven wire mesh screens of at least 1.5 mm wire, with openings not greater than 15 mm for placement within 100 mm of moving parts. Guards may also be made with woven wire mesh of 2.7 mm wire and 50 mm openings.

9.1.15 Fans that have been tested and rated according to IS 2312 are recommended. It may be noted, however, that fans may be tested with or without guards and louvers in place. It shall be ensured that the fans provide the required capacity with guards and louvers installed.

9.2 Evaporative Pad Cooling

9.2.1 Evaporative pads are commonly used to aid greenhouse cooling in warm climates by lowering the dry bulb temperature of the inlet air. Pads and inlets sized to maintain the face velocities presented in Table 3 may be expected to reduce inlet air temperature to within 2.0°C of the outside wet bulb temperature at pressure drops through the pads not exceeding 15 Pa. Temperature rise in a house cooled with evaporative pads may generally be greater, all other things being equal, than in a house where evaporative pads are not used; however, average inside temperatures will generally be significantly lower.

Table 3 Recommended Air Velocities Through Various Pad Materials

Sl No.	Material Type	Face Velocity of Air Through Pad (m/s)
i)	Aspen fibre mounted vertically: 50-100 mm thick	0.75
ii)	Aspen fibre mounted horizontally: 50-100 mm thick	1.00
iii)	Corrugated cellulose: 100 mm thick	1.25
iv)	Corrugated cellulose: 150 mm thick	1.75

9.2.2 Exhaust fans used with evaporative pads shall be sized to provide the required airflow rate at an overall static pressure drop of 30 Pa. The preferred pad-to-fan distance is 30 to 45 m, but the limit is generally end-wall area. For very long houses where end wall area is limiting, installing fans in the roof or walls at midpoint and pads at both ends may prove acceptable, although a stagnant hot spot may form at the midpoint of the house in this configuration.

9.2.3 Pads may be installed in a continuous line along the side or end of the house opposite the exhaust fans. Vertical height shall neither be more than 2.5 m nor less than 0.5 m to insure uniform wetting of the pads.

9.2.4 Pads may be mounted vertically or horizontally. In either orientation, aspen pads shall be well supported to prevent sagging. Provision may be made to allow inspection to detect algae growth, salt buildup, or the development of thin spots or holes in aspen pads, or dry spots in corrugated pads. Any of these conditions may result in a significant reduction in cooling efficiency.

9.2.5 Air inlets shall be constructed so that they can be easily covered during winter without removing the pads.

9.2.6 When possible, pads may be located on the side of the house from which prevailing summer winds originate, unless greenhouse is sheltered by another building or greenhouse within 10 m.

9.2.7 Fans may not exhaust directly into pads inlets unless the distance between fan and the inlet is more than 15 m.

9.2.8 Fans may not exhaust directly into each other. Opposing fans may be offset from each other unless they are more than 4-5 fan diameters apart.

9.2.9 Cooled air tends to sink; therefore, vertical baffles above the plant growing area are not necessary or recommended. Sometimes baffles covering the lower two-thirds of the area under benches are installed for better cooling at bench height.

9.2.10 Recommended minimum water flow rates and sump capacities for vertically mounted pads are listed in Table 4. These rates may be sufficient to insure that the pads remain wet from top to bottom, provided that the pads have been sized according to Table 3.

Table 4 Recommended Water Flow and Sump Capacities for Vertically Mounted Cooling Pads

Pad Type and Thickness	Minimum Water Flow Rate per Unit Length of Pad l/min.m	Minimum Sump Capacity per Unit Pad Area l/m^2
Aspen fibre (50-100 mm)	4	20
Aspen fibre, desert conditions (50-100 m)	5	20
Corrugated cellulose (100 mm)	6	35
Corrugated cellulose (150 mm)	10	40

9.2.11 Horizontal pads shall be watered at a constant rate close to the evaporation requirements. The maximum recommended rate is 0.2 l/s.m^2 of pad area. Lower rates may be achieved by intermittent operation of the pad irrigation system.

9.2.12 The water returned to the sump may be screened to filter out pad fibres and other debris. A 50 mesh screen size inclined screen mounted below the return flow is effective. The sump shall be covered to protect it from insects and other debris. Removable caps or valves may be installed on the ends of the water distribution pipes (located over the pads) to allow periodic flushing.

9.2.13 As water evaporates, the salt concentration in the sump increases. In areas that have water with high mineral content, a bleed-off rate of 0.02 l/min per m^3/s of airflow will minimize salt buildup.

9.2.14 It is preferable to protect the pad assembly by installing it inside any air inlet openings. The air inlet opening need not be continuous but should be uniformly distributed across the house.

9.2.15 If the pad assembly is located outside an inlet, the opening shall be continuous, have no large obstructions and be centered in relation to the pad. Maximum design velocities through the inlet shall be limited to 2.0 metre per second.

9.2.16 When the height of the pad exceeds that of the inlet, the pad may be set back from the inlet by a minimum of half the height difference.

9.3 Fog Cooling

9.3.1 Fog has long been used to supplement cooling when the ability of the plants to transpire is expected to be impaired (for example, in rooting and transplant houses).

9.3.2 Fog is generally produced using a high pressure pump to atomize water by forcing it through fixed nozzles distributed throughout the house or nozzles attached to tips of rotating fan blades. Atomization may also be accomplished by a rotating disk or acoustic oscillator. The atomized water droplets shall be 0.5 to 50 microns to insure proper cooling.

9.3.3 Fog may be distributed through fixed nozzles located appropriately throughout the house, through perforated poly-tubes or using horizontal air circulation systems.

9.3.4 Good quality water is needed for fogging systems. The water shall be free of precipitate and salts.

9.3.5 In naturally ventilated greenhouses, nozzles should be uniformly spaced throughout the house. Pipes and nozzles may be located over aisles to prevent water dripping directly onto plants.

9.3.6 In fan cooled houses, most of the fog should be concentrated near the inlet with a small amount distributed evenly over the rest of the house.

9.4 Shading

9.4.1 The use of shading to aid in cooling is not without problems; however, in some circumstances it may provide the only alternative to suspending operation during the hottest part of the year. Most shading is accomplished using porous, woven, or knitted materials, usually plastic, placed on top of the greenhouse cover (external) or suspended between the gutters (internal) in ridge and furrow houses or mounted parallel to the roof line. Shade cloths are typically green, black, white, or aluminized.

9.4.2 The ability of shade materials to control temperature is limited by the radiant energy they absorb. Black and green external shade cloths have been observed to reduce temperature gains by less than 50 percent of the shade rating (amount of visible radiation blocked). White cloths tend to provide greater temperature reduction but they generally cost 50-100 percent more. Very little information is available on aluminized materials.

9.4.3 Where shade cloths may not be easily retracted during periods of cloudy weather, shade ratings of the cloths used may be carefully chosen to avoid limiting growth. Higher values may be used with shade (low-light) plants or crops with a shallow canopy depth (for example, potted plants on benches). Lower values may be used with taller, more dense crops (for example, mature tomatoes, cucumbers, etc).

9.4.4 State-of-the-art shading systems mount shade cloths in a manner that facilitates automatic extension or retraction as needed (for example, between the gutters or parallel to the roof line). This allows materials with higher shade ratings to be used on both temperature and light levels to avoid shading during hot, hazy periods when light may be limiting.

9.4.5 Shading compounds, sometimes referred to as 'whitewash', may be applied to the outside of greenhouses with some degree of success. Degree of shading is controlled by the thickness of the coating or by application of the material in alternating strips so that only a portion of the glazing is covered. These materials are expected to wear away due to exposure to the weather; however, it is common for physical removal to become necessary as light becomes limiting in late fall. Compounds may be purchased with different degrees of adhesion (lower adhesion levels are recommended for plastic glazings); however, physical removal may be more difficult with flexible plastics (for example, polyethylene film) compared to rigid plastics or glass. Care may be used during application and removal to prevent the compounds from dripping onto foliage through cracks in the glazing.

9.5 Winter Ventilation Considerations

9.5.1 Winter ventilation requirements vary with location and climate more than summer ventilation rates. From 10 to 50 percent of the summer time ventilation requirements or 0.005 0-0.020 $m^3/s.m^2$ of the floor area, may be generally sufficient in cooler climates; however, warmer climatic regions may require more.

9.5.2 If exhaust fans are individually controlled, there should be no need to provide winter ventilation control separate from that for summer ventilation. If individual control is not possible, separate winter ventilation control may have to be provided to prevent the introduction of excessive quantities of cold air into the greenhouse and the resulting possibility of crop damage.

9.5.3 If day time outside temperatures below 5°C are expected, incoming air should be introduced so that it mixes and is warmed by the interior air before contacting the plants. A continuous vent window located high on the wall opposite the fans provides one alternative. In such cases, the inlet shall be sized to provide an air velocity of 3.5 metre per second at the required flow rate. Either perforated-tube or horizontal airflow systems may be used to distribute the cold air within the house so as to maximize mixing before it contacts the plants.

9.6 Venting Controls

9.6.1 It is preferable to control ventilation in multiple stages. If computer control is used, individual control of each exhaust fan is recommended. Where limited numbers of fans are needed, two-speed motors may provide additional flexibility. Fans may be activated sequentially by the control system in response to cooling needs.

9.6.2 The first stage of ventilation shall be at least 4-6°C above the heat setting to prevent heating and ventilating from occurring at the same time.

9.6.3 Solid-state sensors may be used for humidity control, if needed, because of frequent calibration required of the older types of humid states. Humidity sensors may be aspirated.

9.6.4 Control sensors may be suitably located and shielded.

9.6.5 Inlet vents may be controlled so that they are activated in proportion to the number of active fans or in response to the pressure drop generated across the inlet. Experience suggests that the later approach provides superior control in windy conditions if the pressure drop is at least 10 Pa.

9.6.6 Line voltage controls may be used on small installations.

9.6.7 A switch shall be provided with each fan to allow manual override in cases of automatic control failure.

9.6.8 Safety disconnects shall be installed near each fan and pump motor. Some consideration may be given to installing back-up electrical generation in case of power failure, especially for exhaust fans during hot weather but also for other critical power needs.

9.7 Cooling and Ventilating Small Greenhouses

9.7.1 Small greenhouses less than 30 m^2 in floor area may be naturally ventilated using ridge vents and doors (or side vents) or using mechanical ventilation. If mechanical ventilation is used (including evaporative cooling), the following design criteria may be followed:

- summer ventilation rate: 0.06 $m^3/s.m^2$ of floor area;
- evaporative cooling capacity: 0.08 $m^3/s.m^2$ of floor area.

9.7.2 Evaporative cooling may be accomplished with a packaged evaporative cooler for lesser cost and greater operating convenience than with a fan-and-pad system. An exhaust opening (such as, a door or automatic shutter) is required at the end of the house opposite the cooler.

9.7.3 Maximum winter ventilation rates are about half the maximum summer ventilation rates and will be greatest for lean-to houses attached to the east, south or west wall of a building. Two speed fans or natural airflow may be used for ventilation.

ANNEX A

(*Clause* 9.1.3)

DETERMINATION OF SPECIFIC VOLUME AND SPECIFIC HEAT OF THE AIR LEAVING THE GREENHOUSE

A-1 PRINCIPLE

Specific volume and specific heat of the air leaving the greenhouse is determined on the basis of psychrometric data. For the purpose, it is required to assemble psychrometric data in equation form in SI units.

The equations given in this section enable the calculation of all psychrometirc data if any two independent psychrometric properties of an air-water mixture are known in addition to the atomspheric pressure. The equations yield results that agree closely with value given by Keenan and Keyes (1936) and existing psychrometric charts.

Saturation Line. P_s, as a Function of T

$$ln\ P_s = 31.960\,2 - \frac{6\,270.360\,5}{\mathrm{T}} - 0.460\,57\ ln\mathrm{T};$$

[255.38 ≤ T ≤ 273.16]

and

$$ln\ (P_s/R) = \frac{A + B\mathrm{T} + C\mathrm{T}^2 + D\mathrm{T}^3 + E\mathrm{T}^4}{F\mathrm{T} - G\mathrm{T}^2};$$

[273.16 ≤ T ≤ 533.16]
Adapted from Keenan and Keyes (1936)

where

$R = 22\,105\,649.25$

$A = -27\,405.526$

$B = 97.541\,3$

$C = -0.146\,244$

$D = 0.125\,58 \times 10^{-3}$

$E = -0.485\,02 \times 10^{-7}$

$F = 4.349\,03$

$G = 0.393\,81 \times 10^{-2}$

Saturation Line. T as a Function of P_s

$$\mathrm{T} - 255.38 \sum_{i=0}^{i=8} A_i\ \{ln\ (0.001\,45\ P_s)\}^i;$$

[620.52 < P_s < 468 8 396.00]

Steltz and Silvestri (1958)

$A_0 = 19.532\,2$

$A_1 = 13.662\,6$

$A_2 = 1.176\,78$

$A_3 = -0.189\,693$

$A_4 = 0.087\,453$

$A_5 = -0.017\,405\,3$

$A_6 = 0.002\,147\,68$

$A_7 = -0.138\,343 \times 10^{-3}$

$A_8 = 0.38 \times 10^{-5}$

Latent Heat of Sublimation at Saturation

$h_{ig} = 2\,839\,683.144 - 212.563\,84\ (\mathrm{T} - 255.38);$
[255.38 ≤ T ≤ 273.16] Brooker (1967)

Latent Heat of Vaporization at Saturation

$h_{fg} = 2\,502\,535.259 - 2\,385.764\,24\ (\mathrm{T} - 273.16);$
[273.16 ≤ T ≤ 338.72
Brooker (1967)

$h_{fg} = (7\,329\,155\,978\,000 - 1\,599\,596\,408\mathrm{T}^2)^{1/2};$
[338.72 ≤ T ≤ 533.16] Brooker (unpublished)

Wet Bulb Line

$P_{swb} - P_v = B'\ (\mathrm{T}_{wb} - \mathrm{T})$ Brunt (1941)

where

$$B' = \frac{1\,006.925\,4\ (P_{swb} - P_{atm})\ (1 + 0.155\,77 \frac{P_v}{P_{atm}})}{0.621\,94\ h_{fg}};$$

Substitute h'_{ig} for h'_{fg}, where [T_{wb} < 273.16] & [255.38 ≤ T ≤ 533.16]

Humidity Ratio

$H = \frac{0.621\,9\ P_V}{P_{atm} - P_V};$ [255.38 ≤ T ≤ 533.16] & [$P_v < P_{atm}$]

Specific Volume

$V_{sa} = \frac{287\ \mathrm{T}}{P_{atm} - P_V};$ [255.38 ≤ T ≤ 533.16] & [$P_v < P_{atm}$]

Enthalpy

Enthalpy = enthalpy of air + enthalpy of water (or ice) at dew point temperature + enthalpy of evaporation (or sublimation) at dew point temperature + enthalpy added to the water vapour (super heat) after vaporization.

$h = 1\,006.925\,40\,(\mathrm{T}-273.16) - H\,\{333\,432.1 + 2\,030.598\,0\,(273.16 - \mathrm{T}_{dp})\} + h''_{ig}\,H + 1\,875.686\,4\ H\ (\mathrm{T} - \mathrm{T}_{dp});$ [255.38 ≤ T_{dp} ≤ 273.16]

and

$h = 1\,006.925\,40\ (\mathrm{T}-273.16) + 4\,186.8\ H\ (\mathrm{T}_{dp} - 273.16) + h''_{fg}\,H + 1\,857.686\,4\ H\ (\mathrm{T} - \mathrm{T}_{dp});$ [273.16 ≤ T_{dp} ≤ 373.16]

Relative Humidity

$rh = P_v/P_s$

Symbols

h	Enthalpy of air-vapor mixture, J/kg dry air
h_{fg}	Latent heat of vaporization of water at saturation, J/kg

h'_{fg}	Latent heat of vaporization of water at T_{wb}, J/kg h''_{fg} Latent heat of vaporization of water at T_{dp}, J/kg h_{ig} Heat of sublimation of ice, J/kg
h'_{ig}	Heat of sublimation of ice at T_{wb}, J/kg
h''_{ig}	Heat of sublimation of ice at T_{dp}, J/kg
w	Humidity ratio, kg water/kg of dry air
ln	Natural logarithm (base e)
P_{atm}	Atmospheric pressure, P_a
P_s	Saturation vapour pressure at T, P_a
P_{swb}	Saturation vapour pressure at T_{wb}, P_a
P_v	Vapor pressure, P_a
rh	Relative humidity, Decimal
T	Dry bulb temperature, kelvin
T_{dp}	Dew point temperature, kelvin
T_{wb}	Wet-bulb temperature, kelvin
V_{sa}	Air specific volume, m^3/kg dry air

ANNEX B

(Foreword)

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